

Biogas potential, utilization and countermeasures in agricultural provinces: A case study of biogas development in Henan Province, China

Mingxue Gao^{a,b}, Danmeng Wang^{a,b}, Hui Wang^c, Xiaojiao Wang^{a,b}, Yongzhong Feng^{a,b,*}

^a College of Agronomy, Northwest A&F University, Yangling 712100 Shaanxi, China

^b Shaanxi Engineering Research Center of Circular Agriculture, Yangling 712100, Shaanxi, China

^c College of Forestry, Northwest A&F University, Yangling 712100 Shaanxi, China

ARTICLE INFO

Keywords:

Biogas potential
Agriculture waste
Resource utilization
Countermeasures
China

ABSTRACT

With climate change and the over-exploitation of fossil fuels, the advantages of using bioenergy are becoming increasingly obvious and many countries and regions around the world are committed to building biogas plants to produce clean energy. This article examines Henan Province, which features agricultural production and biogas projects typical of China. The aim was to identify the problems associated with the use of current agricultural waste in biogas production and provide suggestions for future biogas developments via comparisons of the potential of agricultural wastes with biogas project construction. Straw and manure volumes were analyzed by using crop yields and livestock production to calculate the biogas potential and the status quo was reflected through biogas project data. Subsequently, biogas potential and projects were analyzed from quantitative and spatial perspectives and a benefit evaluation was conducted. The results indicate that Henan Province has abundant straw and manure resources with large biogas potential, and that making good use of these wastes would have a good emission reduction effect and economic advantages, but there are presently large differences between the actual production and biogas potential. This paper analyzes the possible causes of this discrepancy, including resource utilization and biogas project operations. Lastly, countermeasures were proposed, such as developing matching technologies, improving relevant policies, and improving ecological-economic benefits to enhance future biogas project development.

1. Introduction

With the development of agriculture and animal husbandry production, the high densities of plantings and livestock have provided people with rich, healthy food. and economic benefits, but such a situation has also brought about a series of resource and environmental problems [1]. For example, research has shown that fecal contamination has become a major water pollution problem, and such contaminants also pose threats to soil and atmospheric health [2,3]. Biogas technology represents an effective method for utilizing agricultural waste and reducing environmental pollution [4]. As the fourth largest energy source in the world [5], biogas utilization reduces waste disposal costs while reducing CO₂ emissions [6]. Thus, it can alleviate two major problems driving environmental deterioration and the energy crisis [7–9]. At present, countries all over the world have attached great importance to the development of biogas. As early as 2009, the

European Union indicated that biogas production would account for 25% of the total biogas production in this region [10]. Among these countries, Germany has been the world leader in the biogas engineering field. There were 10,786 biogas projects completed in Germany, accounting for 62.6% of those in Europe, by 2014, and the country's renewable energy act has been amended four times to promote such projects [11]. In 2010, the Asian Development Bank (ADB) approved a 6.6 million USD loan to support China's promotion of biogas energy [12]. In the same year, China's annual biogas output rose to 248 billion cubic meters [13]. China is rich in biomass resources, which include crop residues, livestock manure, forest residues, and various municipal and industrial organic wastes [14,15]. All of these can be used as raw materials for energy production, and so China has huge biogas potential. According to the 2014 China Statistical Yearbook, the output of major cereal products in Henan Province was 55.227 million tons, and the output of meat reached 69.91 million tons, both ranking first in the

Abbreviations: SBP, straw biogas potential; SGR, straw grain ratio; MBP, manure biogas potential; UNFCCC, United Nations Framework Convention on Climate Change; ADB, Asian Development Bank; CDM, Clean Development Mechanism

* Corresponding author at: College of Agronomy, Northwest A&F University, Yangling 712100 Shaanxi, China.

E-mail address: fengyz@nwsuaf.edu.cn (Y. Feng).

<https://doi.org/10.1016/j.rser.2018.10.005>

Received 17 May 2018; Received in revised form 19 September 2018; Accepted 3 October 2018

Available online 19 October 2018

1364-0321/ © 2018 Elsevier Ltd. All rights reserved.

country [16,17]. Therefore, this article has selected Henan Province as the focal point of the biogas analysis. In addition, China has a huge demand for fossil fuels. However, the use of fossil energy has serious impacts on the environment. Biogas, which is a clean energy source, can effectively alleviate this situation. However, biogas plant operations also face problems such as inefficient and improper operations, and it is presently difficult for biogas to truly play an important role in saving resources and protecting the environment as an alternative energy source.

Previous studies on biogas have mainly focused on the fermentation process, microbial communities, equipment optimization, etc [18–21]. To date, there are few studies on the raw materials and production potential based on quantitative and spatial analyzes, as well as emission reduction assessments. In this paper, Henan Province was chosen as a study area to examine agricultural production and biogas project construction in China. The crop yield and livestock yield were used to compute the straw and manure volume and calculate the agriculture waste biogas potential, and then, the current situation was assessed with the biogas project data. A discussion is presented of the biogas potential and utilization degree in typical areas, and an effort was made to identify problems in biogas development to provide a reference for making improvements to the biogas industry in the future.

2. Materials and methods

2.1. Data sources

Crop production and livestock herding data for Henan Province from 2009 to 2014 were procured from the China Statistical Yearbook and the Henan Province Bureau of Statistics. Biogas project data were provided by the Henan China Energy Regulation Bureau. Charts in the text were drawn by using OriginPro2016 and ArcGIS10.2 software.

2.2. Straw biogas potential (SBP)

According to previous research for different types of crop straw, the straw biogas potential (SBP) (m^3) for biogas production can be estimated for 90 d of anaerobic fermentation under 35°C reaction conditions by using Eq. (1) [22].

$$\text{SBP} = S_i \cdot a_i \quad (1)$$

where S_i is the stalk yield (kg) of crop i , and a_i is a stalk biogas conversion parameter derived from previous studies (Table 1) [23,24]. S_i values are not included in the data from the statistical bureaus; therefore, these values are usually calculated from the crop yield C_i (kg) and straw grain ratio (SGR) by using Eq. (2), in which R_i is the SGR for a given crop (kg/kg):

$$S_i = \sum_i^n C_i \cdot R_i \quad (2)$$

Previous estimates of crop straw production in Henan Province were retrieved from the published literature and used for the SGR [24]; the average SGR values used herein are shown in Table 2 [25–29].

2.3. Manure biogas potential (MBP)

Many factors involved in the production process affect the

Table 1
Crop straw related parameters.

Corp	Rice	Wheat	Corn	Legume	Tubers	Cotton	Oil-bearing
a_i (m^3/kg)	0.40	0.45	0.50	0.40	0.40	0.40	0.40
S_i (kg/kg)	1.3	1.1	1.5	1.6	0.8	5.4	2.0

Note: Parameters of legume, tubers, cotton, oil-bearing refer to rice conversion parameters.

Table 2
Livestock related parameters.

Livestock	Pig	Cattle	Sheep	Poultry
b_i (m^3/t)	60	45	62	80
d_i (kg/(head·d))	2.15	21.01	1.11	0.10
m_i (d)	199	160	150	45

production of biogas from livestock manure. Previous studies have suggested the following livestock manure biogas conversion parameter and formula for estimating the manure biogas potential (MBP) (m^3):

$$\text{MBP} = M_i \cdot b_i \quad (3)$$

where M_i is the amount of livestock manure produced (kg) from livestock i , and b_i is the livestock manure biogas conversion parameter.

M_i was calculated according to the method reported by Gao [25].

$$M_i = \sum_i^n Q_i \cdot d_i \cdot m_i \quad (4)$$

where Q_i is the total number of livestock, d_i is the excretion coefficient (i.e., the daily excretion of each animal), and m_i is the animal husbandry period, in which the inventory span is 365 d and the slaughter date varies. Actual livestock breeding data from previous studies were used to determine the parameters used herein as shown in Table 3 [30–34].

2.4. Biogas-standard coal conversion

The formula for converting biogas into standard coal is as follows:

$$Q_C = Q_B \cdot E \quad (5)$$

where Q_C (kg) and Q_B (m^3) represent the amount of standard coal and biogas, respectively, and E is the conversion coefficient of biogas to standard coal, for which the value amounts to $0.714 \text{ kg}/\text{m}^3$ [35].

2.5. Carbon dioxide emissions

Wang et al. [36] proposed a method for calculating CO_2 emissions. The CO_2 emissions from biogas combustion are as follows:

$$C_B = 3.67 \cdot B \cdot q_B \cdot E_B \quad (6)$$

where B is the biogas consumption, q_B denotes the calorific value of biogas, for which the value is $0.209 \text{ TJ}/10^4 \text{ m}^3$, E_B is the carbon emission factor of $15.3 \text{ t}/\text{TJ}$, and 3.67 represents the ratio of the CO_2 molecular weight to C atomic weight.

The CO_2 emissions from standard coal combustion can be calculated as follows:

$$C_C = 3.67 \cdot C \cdot q_C \cdot E_C \cdot 89.9\% \quad (7)$$

where C is the standard coal consumption, q_C denotes the calorific value of biogas and is $0.0209 \text{ TJ}/\text{t}$, E_C is the carbon emission factor of $24.26 \text{ t}/\text{TJ}$, 3.67 represents the ratio of the CO_2 molecular weight to C atomic weight, and 89.9% is the standard coal oxidation rate.

Table 3
Quantity of livestock slaughter and inventory in breeding industry (10^6 head).

	2009	2010	2011	2012	2013	2014
Poultry	900.87	943.32	943.59	888.50	851.02	805.13
Pig Inventory	44.20	44.27	45.87	45.69	45.47	45.29
Pig Slaughter	63.10	59.97	57.11	53.61	53.91	51.44
Cattle Inventory	9.18	9.05	9.08	9.55	10.1	10.45
Cattle Slaughter	5.46	5.36	5.35	5.45	5.52	5.60
Sheep Inventory	18.86	18.30	18.28	18.65	18.95	19.97
Sheep Slaughter	20.88	20.32	20.27	20.50	21.15	21.76
Total	1062.55	1100.59	1099.55	1041.95	1006.12	959.62

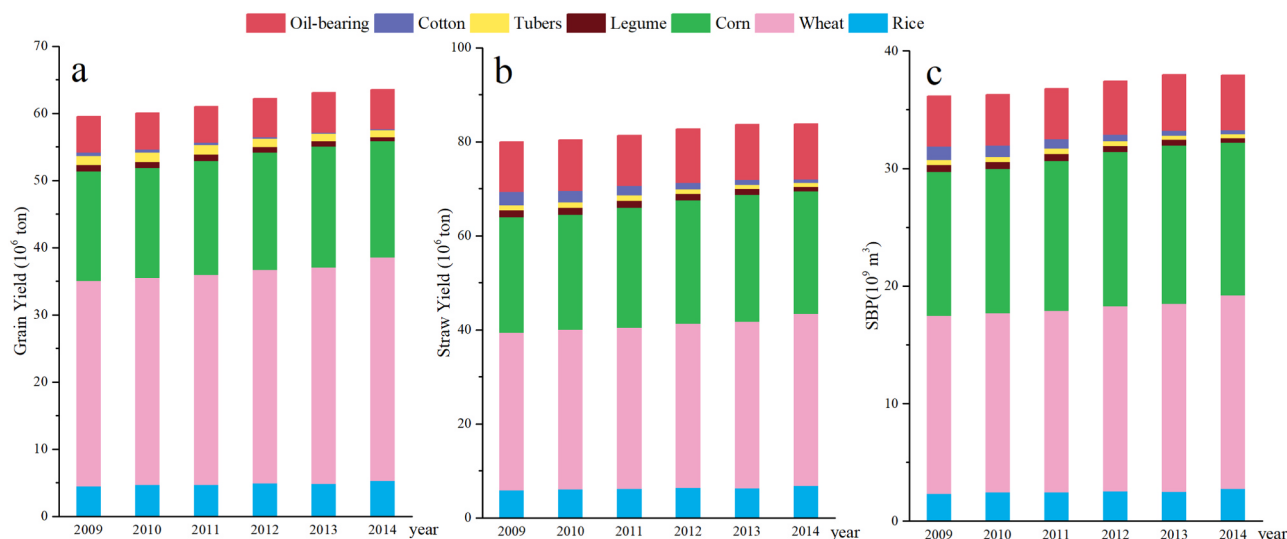


Fig. 1. SBP various parameters during 2009–2014 in Henan province. Note: Fig. a shows different crop's grain yield. Fig. b shows different crop's straw yield. Fig. c shows different crop SBP.

3. Results and discussion

3.1. Analysis of the biogas potential of agricultural waste

3.1.1. Biogas potential quantitative characteristics

SBP is prominent in biogas of agricultural waste. As shown in Fig. 1, the annual output of major crops from 2009 to 2014 in Henan Province measured 60 Mt. Wheat and corn were the major crop products, and these made up more than 51% and 27% of the total production yield, respectively. The proportions of various crop types affect the straw yield and, thus, influence the biogas potential; but the proportions of different crops are related to the local planting structure. This relationship can be seen when comparing yields with SBP values. The annual average SBP was $37.093 \times 10^9 \text{ m}^3$, with a trend of steady yearly growth for crop stalks converted into biogas under 35°C fermentation conditions. However, the share of biogas potential varied greatly between the different crop straws. For instance, the biogas potential of wheat straw accounted for 42.24% of the total potential value, followed by 34.50% for corn stalks, and tuber straw featured the lowest potential with an average of only 1.09%. These results are related to the planting structure in Henan Province.

The total number of MBP and domestic animals bred in Henan Province did not change significantly from 2009 to 2014. And the amount of manure excreted annually within the livestock industry averaged 166.41 million tons (Table 3). As can be seen in Fig. 2, pig and cattle dung were the major components of livestock manure discharge, accounting for 90.92% of the total manure discharge, and these findings were related to the growth characteristics of the animals. The MBP was positively correlated with the manure volume, and so the MBP volume and structure did not change significantly.

The 6-year average MBP values were $3.58 \times 10^9 \text{ m}^3$ for pigs, $4.13 \times 10^9 \text{ m}^3$ for cattle, $0.69 \times 10^9 \text{ m}^3$ for sheep, and $0.32 \times 10^9 \text{ m}^3$ for poultry. While poultry manure was discharged in the lowest amounts, it also will be important to develop this resource in order to maximize its potential. On the whole, agriculture waste was widely produced and showed great potential for biogas potential (Table 4).

3.1.2. Biogas potential spatial characteristics

Estimations of crop straw biogas potential and analysis results for the SBP spatial distribution are shown in Fig. 3 for 18 cities in Henan Province in 2014. The five cities with the highest potentials had SBP values of $4.936 \times 10^9 \text{ m}^3$ (Zhoukou City), $4.427 \times 10^9 \text{ m}^3$ (Zhumadian City), $3.732 \times 10^9 \text{ m}^3$ (Nanyang City), $3.590 \times 10^9 \text{ m}^3$ (Shangqiu

City), and $2.437 \times 10^9 \text{ m}^3$ (Xinxiang City). The enormous crop yields in these five cities led to an abundance of crop stalks, which in turn yielded very high biogas potentials conducive to the development of biogas projects that use crop straws as the main anaerobic fermentation substrate.

According to the overall data, the MBP was highest in Zhumadian City in 2014 at $933 \times 10^6 \text{ m}^3$, which accounted for 12.77% of the total potential value; Zhumadian City was followed by Nanyang City, Zhoukou City, Shangqiu City, and Xinyang City in potential. The gasification potential of livestock in these five cities accounted for 52.49% of the total potential value. Jiyuan City had the lowest biogas potential with an MBP of only $42 \times 10^6 \text{ m}^3$ (Fig. 4). It can be seen from Table 6 that the biogas potential of various cities in Henan Province was quite different. In short, the potential of biogas in Henan Province is huge, but the potential of individual cities is unevenly distributed.

3.2. Benefit evaluation of biogas potential

The benefits of biogas production can be analyzed in terms of techno-economic and environmental benefits. In Germany, as result of increased value added through biogas production and high competition among farms, rental prices have increased and biogas production has had positive effects on the labor market as biogas farms have produced additional workforce demands [37]. Heat prices received by biogas plants are up to a mean revenue of 2.39 USD/kW h on the plant level [38]. However, there is a gap between China's biogas development and that in developed countries. In the realm of rural, domestic biogas, the economic benefit level is at the medium level, and the energy efficiency and ecological efficiency are good, but social benefits are only general in nature. The comprehensive evaluation showed that such a situation was close to the good level [39]. However, in terms of actual production, most of the plants can only breakeven or achieve slight profits, and raw material costs represent the main costs. Thus, straw biogas projects lack economy feasibility without the support of government investments [40]. The average biogas cost excluding the initial investment is 0.11 USD/ m^3 , and the price is 0.22 USD/ m^3 in China [41]. From the perspective of this paper, the biogas production of Henan Province in 2014 yielded a profit of 5.13 billion dollars, and if the costs of raw materials can be reduced, the economic benefits of biogas will be further improved.

Along with analyzes of global warming, the United Nations Framework Convention on Climate Change (UNFCCC) has called for countries to undertake emissions reductions. Since 2007, China has

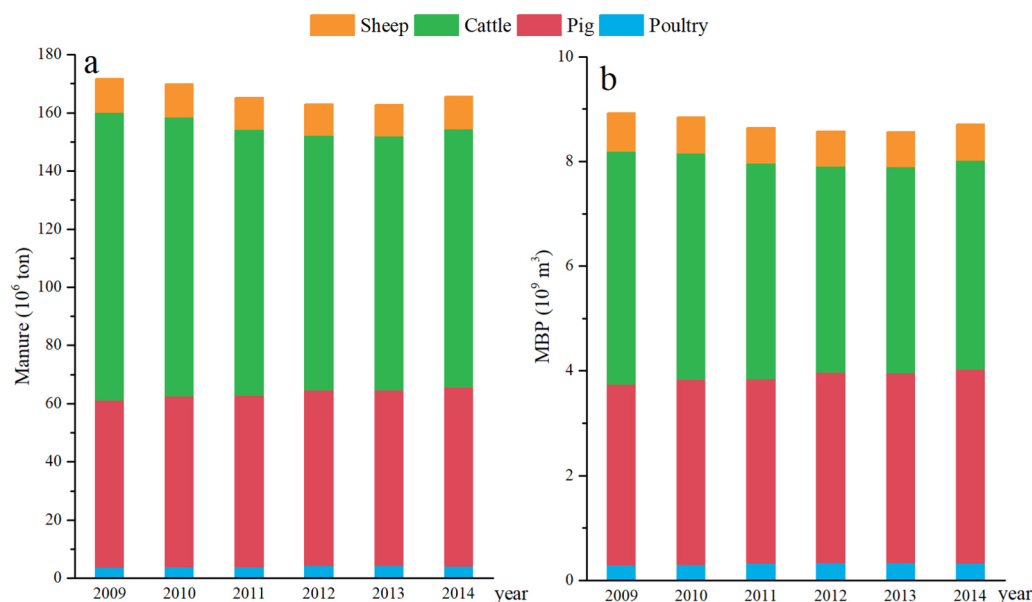


Fig. 2. MBP various parameters during 2009–2014 in Henan Province. Note: Fig. a shows different livestock manure output. Fig. b shows different livestock MBP.

Table 4

Biogas potential data of Henan province in 2009–2014.

	SBP	MBP	Total Potential	Biogas CO ₂ emission	Equivalent to standard coal	Standard coal CO ₂ emission
	(10^9 m ³)	(10^9 m ³)	(10^9 m ³)	(10^9 t)	(10^9 t)	(10^9 t)
2009	36.140	8.921	45.061	0.053	0.032	0.195
2010	36.294	8.847	45.141	0.053	0.032	0.196
2011	36.789	8.648	45.437	0.053	0.032	0.197
2012	37.442	8.577	46.019	0.054	0.033	0.199
2013	37.957	8.566	46.523	0.055	0.033	0.202
2014	37.935	8.709	46.644	0.055	0.033	0.202

been the world's largest emitter of greenhouse gases, and China attaches great importance to this situation [42]. The extensive use of fossil fuels has also brought about severe pollution problems locally. The energy consumption data show that Henan Province has formed a coal-dominated, multi-resource-assisted energy structure (Table 5). At the same time, this has had a serious impact on the environment, as key pollutants including sulfur dioxide, suspended particles, nitrogen oxides, and carbon dioxide are released [43]. The use of biogas has the dual benefits of reducing emissions and protecting the environment. In the case of agriculture waste converted to biogas in Henan Province, it was equivalent to 321–332 million tons of standard coal during 2009–2014. The further application of biogas potential in practice could reduce the over-exploitation of non-renewable resources. The analysis data indicated that the annual reduction in carbon dioxide emissions could reach 1.4 billion tons (Table 4). This result would correspond to a positive effect on global warming.

3.3. Biogas project construction status and characteristics

The role of biogas projects in a circular agricultural model is to extend the food chain and facilitate the reuse of agro-resources to realize multilevel energy utilization [44]. The number of biogas projects may be related to the agricultural, animal husbandry, and economic conditions as well as policy support in a given city. Medium- and large-scale biogas projects in Henan Province grew steadily between 2009 and 2014. This timing is related to policy and economic development [45], such as the completion of the “11th 5-year Plan” (2006–2010), which included key ecological protection projects and

new countryside construction, and the State's “12th 5-year Plan,” which promoted the specialization, standardization, capacity enhancement, and intensive construction and development of agricultural production and management. A certain number of projects were successfully constructed and put into operation each year. As shown in Table 7, the year 2011 featured the lowest investment and construction, while 2014 featured the largest investment. A total of 105 investment projects were constructed from 2009 to 2011, while a total of 150 investment projects (excluding ADB investments) were constructed from 2012 to 2014. Fig. 5 shows the spatial variation of these projects. Xinxiang City had 35 projects, followed by Zhoukou City and Nanyang City with 31 and 28, respectively; Puyang City, with only 4, has the fewest biogas plants.

In the 2009–2014 period, a total of 278 medium- or large-scale biogas projects were constructed in Henan Province, with a total gas production value of 72.58×10^6 m³. If the generated biogas is completely and effectively burned, it will save 41.02×10^6 kWh of electricity and reduce carbon dioxide emissions by 356,700 t. Biogas produced by these projects was supplied to 77,107 households during 2009–2014 and produced a total annual power generation amount of 32,821,800 kWh. These biogas projects not only resolved some of the energy issues experienced by farmers, but also reduced financial expenditures and, to a certain extent, mitigated the environmental problems caused by the use of fossil fuels, thereby making positive contribution to ecological health.

3.4. Comparison of the biogas potential and projects

Biogas projects are practical solutions for the treatment of agricultural wastes. Furthermore, assessments of the biogas potential of waste can be used to outline the ideal situation for all waste to be used in biogas production. However, there is often a huge gap between the ideal and reality. Problems in the development of biogas can be found by analyzing the current situation.

Through comparing the quantitative data between the biogas potential and projects, the biogas potential as a percentage of actual production was found to be 0.01% in 2010, after which it increased; there was little fluctuation after 2012, possibly because the factors for the livestock industry, waste biogas potential, and construction industry, which affecting the ratio after 2012, tended to stabilize (Table 8). This shows that the actual production effect of biogas plants is very small compared with the biogas potential. The plant operational

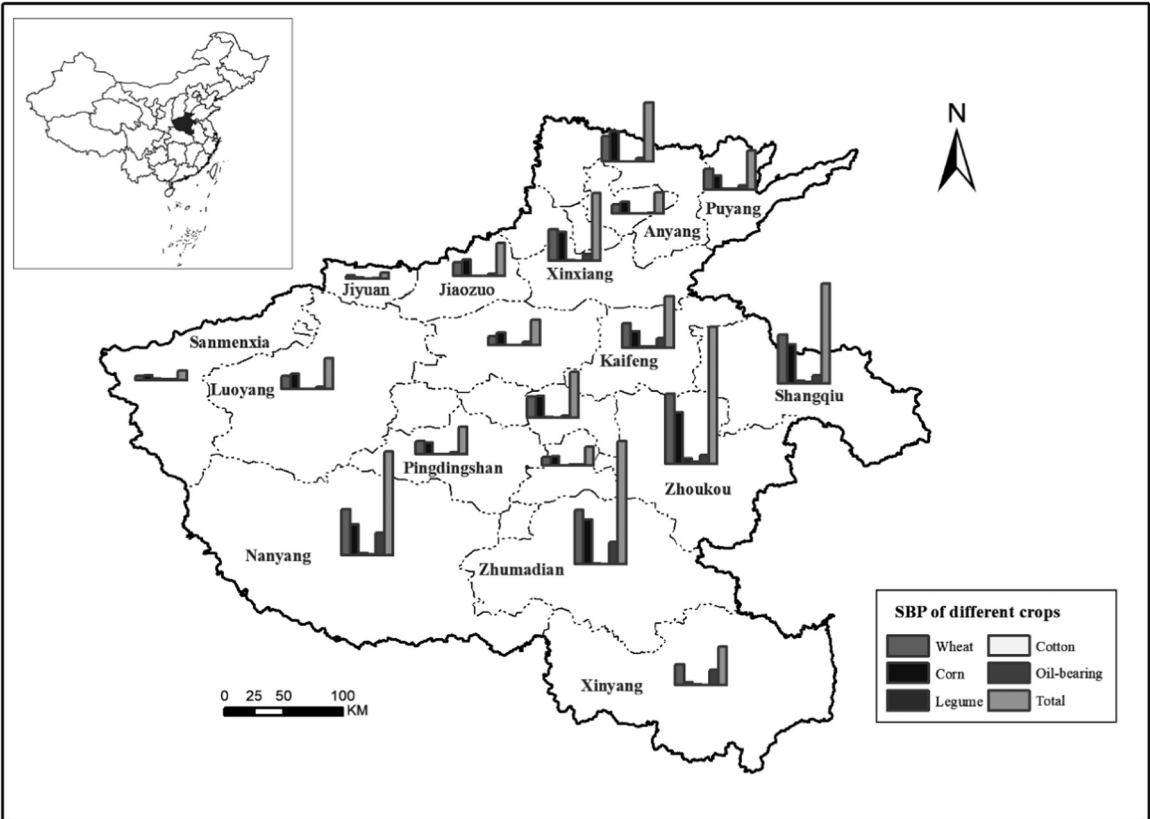


Fig. 3. 18 cities in Henan province SBP spatial distribution.

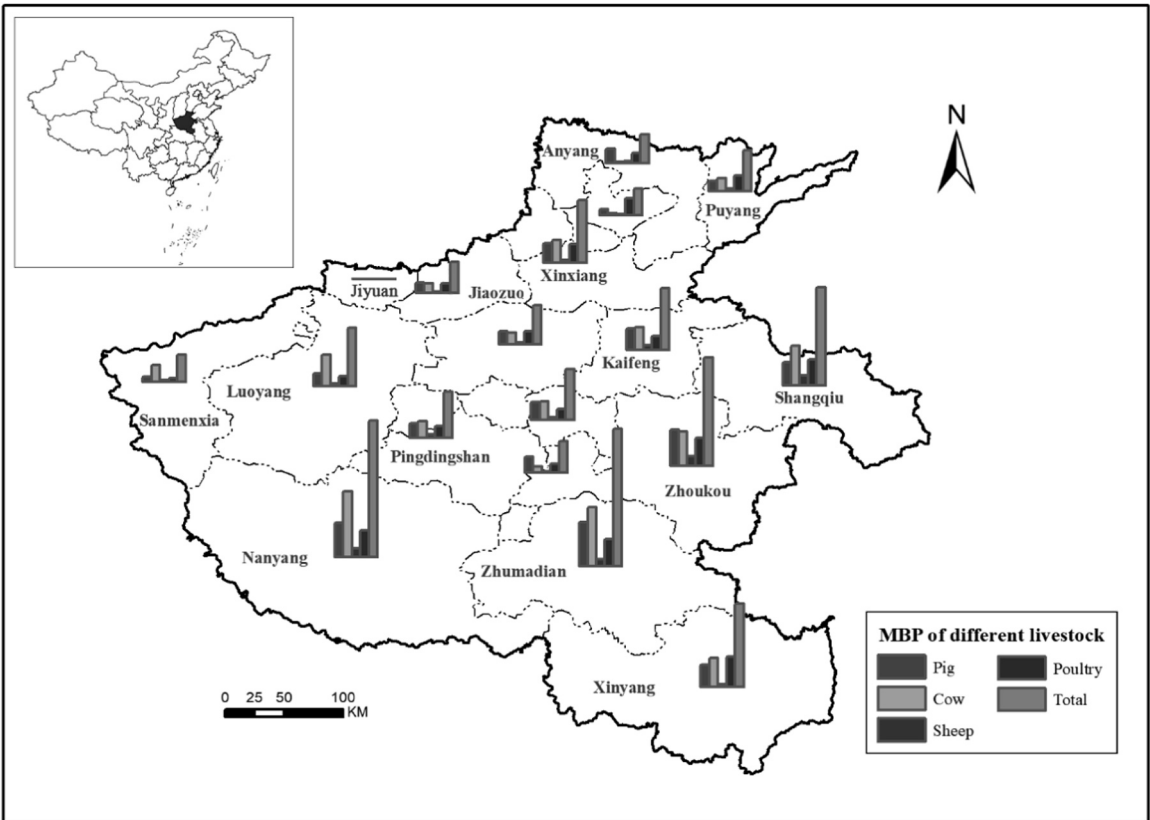


Fig. 4. 18 cities in Henan province MBP spatial distribution.

Table 5
Energy consumption of Henan province in 2009–2014 (million tons).

	2009	2010	2011	2012	2013	2014
Coal	244.45	260.50	283.74	252.40	250.58	242.49
Coke	14.42	17.43	20.53	22.22	18.17	27.01
Crude	7.86	8.35	8.75	10.10	9.64	8.45
Gasoline	1.96	2.97	3.59	4.27	5.57	5.29
Kerosene	0.26	0.31	0.49	0.53	0.46	0.50
Diesel	5.26	5.61	6.63	7.38	7.78	8.01
Fuel oil	0.26	0.18	0.42	0.13	0.34	0.49

Table 6
The quantitative statistics of biogas in 18 cities, 2014 (10^9 m^3).

City	SBP(10^9 m^3)	MBP(10^9 m^3)	Total potential(10^9 m^3)	Projects number
Zhoukou	49.36	7.39	56.75	29
Zhumadian	44.27	9.33	53.60	23
Nanyang	37.32	9.31	46.63	26
Shangqiu	35.90	6.68	42.58	15
Xinxiang	24.37	4.26	28.63	31
Anyang	21.33	1.95	23.28	13
Kaifeng	18.51	4.17	22.68	10
Xuchang	16.67	3.46	20.13	7
Xinyang	13.75	5.64	19.39	17
Puyang	13.87	2.77	16.64	4
Luoyang	11.30	4.00	15.31	9
Jiaozuo	11.92	2.12	14.05	12
Pingdingshan	10.06	3.11	13.17	8
Zhengzhou	9.04	2.65	11.69	29
Hebi	7.54	1.83	9.38	14
Luohe	6.57	2.11	8.68	9
Sanmenxia	3.46	1.85	5.31	11
Jiyuan	0.01	0.42	0.43	5

Table 7
Operational status of biogas project of Henan province in 2009–2014.

	Projects Number	Biogas Yield ($10^5 \text{ m}^3/\text{y}$)	Household Number
2009	33	/	/
2010	50	502.05	7427
2011	22	596.16	8171
2012	51	1629.15	18,807
2013	46	1491.95	18,794
2014	53	1884.33	22,808
ADB Investment	23	1154.46	1100
Total	278	7258.1	77,107

Note: Due to a large amount of biogas projects construction started in 2009, some data lack.

efficiencies were low, and the agricultural waste in Henan Province was underutilized. Based on the comprehensive analysis of the spatial distribution of crop stalk and livestock excrement resources in terms of the biogas potential in combination with the construction of biogas projects in Henan Province, it was obvious that the actual biogas production was spatially inconsistent with the biogas potential (Table 6). In particular, the situation in Shangqiu City differed from the distribution trends of well-developed biogas projects. This means that biogas is not having the expected environmental and economic benefits.

3.5. Biogas utilization issues

The difference between biogas potential and actual biogas production can be attributed to both raw material use and biogas engineering.

3.5.1. Resource utilization issues

The agricultural and livestock waste resource utilization rate was

low in the biogas projects. The reasons for this phenomenon are various. First, there are numerous ways to utilize agricultural and livestock waste resources in Henan Province; use is not limited to biogas fermentation. The main utilization pathways include centralized gasification (pyrolysis, gasification, and biogasification), straw solidification, carbonized straw, and so on [46–48]. Second, the actual biogas production process involves high collection effort, transport costs, and waste consumption. Currently, the economic benefits brought about by the use of the waste cannot be harmonized with the costs [40]. Those cost pressures have made farmers and businesses reluctant to spend large amounts of money on waste utilization. Finally, the use of waste includes both raw materials and leftovers in the production process. In the production process, great attention is given to biogas production, while the biogas slurry and residue generated during the operations are not considered seriously [49,50]; some enterprises handle these by-products improperly, sometimes directly discharging them into the environment, which leads directly to resource waste and environmental pollution.

3.5.2. Biogas project operation issues

Biogas fermentation involves the decomposition of the substrate by microorganisms under anaerobic conditions into methane, carbon dioxide, and water. Due to the influence of fermentation conditions, substrate characteristics, and the fermentation process, biogas projects can have low gas production efficiencies. Numerous technologies that increase the biogas production efficiency have been proposed in experiments, but these are not yet applicable at full production scales; At present, these technologies tend to be suitable either for only a particular biogas project or in suitable regions. These limitations greatly reduce their level of promotion and application. Additionally, biogas is used mostly for cooking, lighting, heating, and providing gas supplies to nearby residents, and thus, power generation is an important part of comprehensive biogas utilization; however, the failure of biogas engine products can cause secondary environmental pollution during biogas power generation [51].

Lastly, the construction and operation of biogas plants is closely related to the supply of raw materials. When the raw material is in short supply, the production efficiency is low or even nonexistent. Raw materials are often scarce during winter, so biogas production often slows during that time. The distribution and construction of biogas projects are not consistent with the crop waste availability, which contributes to raw material shortages. This system is out of step with actual agricultural production, and therefore it cannot efficiently digest waste. In order to achieve efficient resource use, biogas production facilities must be well stocked with raw materials.

4. Proposed solutions for biogas production issues

4.1. Develop matching technology

The development of matching technology is the key to improving the efficiency of raw materials and biogas productivity. Presently, many researchers have improved fermentation processes to increase yield [52–54]. Beyond that, suggestions are given below from the two perspectives of management technology and application technology. Although the development of large- and medium-scale biogas projects in Henan Province started late, the development momentum is fierce, and the entire biogas production industry chain consists of raw materials processing, anaerobic fermentation, purification, power generation, and many other aspects related to equipment; overall, the system is very complicated. In fact, many managers are not fully aware of the repair and safety issues. Some biogas digesters have been plagued by low utilization rates, inadequate maintenance, and poor management systems during operation. As far as management technology is concerned, there needs to be strengthened supervision of waste collection and transportation, and staff and management training are needed to

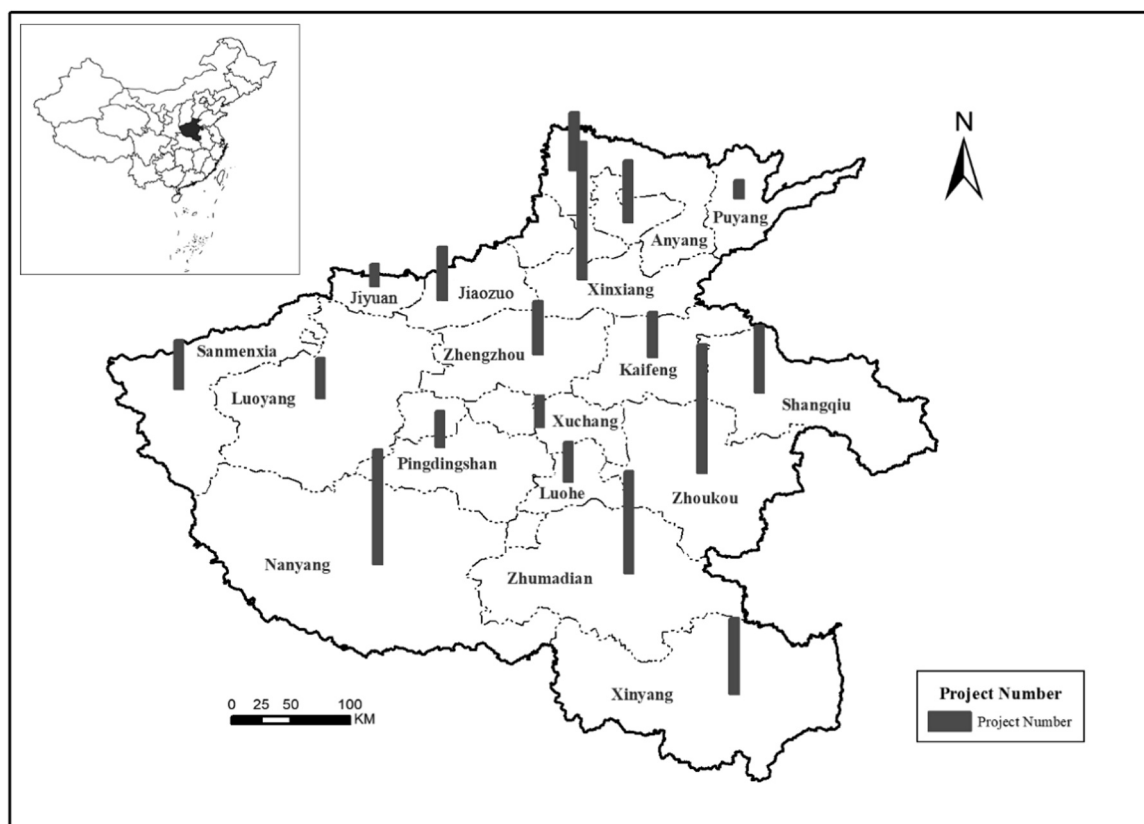


Fig. 5. Middle- or large-scale projects spatial distribution in Henan province.

Table 8

Actual production and potential comparison.

	2009	2010	2011	2012	2013	2014	Total
Biogas potential (10^5 m^3)	450.61	451.41	454.37	460.19	465.23	466.44	2748.25
biogas production yield (10^5 m^3)	/	0.05	0.06	0.16	0.15	0.19	0.61
Biogas potential as a percentage of actual production	/	0.01%	0.01%	0.04%	0.03%	0.04%	0.02%

ensure the uniform distribution of biogas projects to solve the problem of insufficient raw material use. Moreover, optimization of the spatial layout could help to improve maintenance and management issues.

The results presented in this study show that the spatial center of fermentation and material production in Henan Province differs slightly from the biogas project distribution, which may be contributing to the higher transportation costs and greater waste of resources. Thus, the biogas project construction design must be improved based on raw material availability and personal management efforts. In addition, practical designs are conducive to the procurement of sufficient supplies of various raw materials and preventing the use of single raw materials, which enables the use of co-digestion and improves the gas production efficiency [55–57]. Adequate preparation and planning should be conducted before construction. Numerous local services and consulting companies have been created and can contribute to efficient biogas project operations [58]. After evaluating the actual production and distribution of agricultural and livestock industries in a given region, planners should select projects that are suitable for the local conditions and give priority to construction in areas with rich waste resources. Simultaneously, management should be strengthened. This approach could help to resolve the issues regarding the supply of raw materials and seasonal material shortages.

In order to ameliorate the low anaerobic fermentation gas production rate, intelligent devices must be improved. Testing of various technologies under real fermentation conditions will reveal the optimal

anaerobic fermentation substrates and conditions. These techniques can then be adjusted for local conditions. Suitable fermentation devices can be chosen for the specific biogas potential composition in a given region in order to improve resource utilization and biogas production efficiency. Note also that the construction of supporting facilities, such as coordinating power generation equipment and biogas production facilities, can promote further progress in biogas power generation. Biogas-driven generation units are suitable for demand-driven electricity generation because of their short start-up periods and ease of control. However, they are not suitable for all biogas fermentation plants, because individual gas appliances require different quality standards. The design of power generation device should be based on actual gas production and the power load of biogas projects [59]. Engineers can also learn from advanced foreign technology and apply model predictions and computer technologies to biogas engineering [60]. Global cooperation should also be pursued vigorously, with a focus on the introduction of advanced biogas purification technologies, remote online monitoring equipment, automatic control systems, and other key equipment.

4.2. Improve relevant policies

The focus areas of supervision and guidance, promotion and popularization, and technical support are all inseparable from the formulation of policy guidelines, which are important for promoting efficient

and sustainable biogas production. Efficient biogas projects can generate huge amounts of bioenergy as well as environmental and economic benefits; therefore, policies are the guaranteed link to developing such technologies and achieving such benefits. Relevant policies include primarily directive and guiding policies, economic inspiration policies, research policies, market policies, and construction policies, which are typically implemented issued gradually [61].

In China, clean energy has been given serious attention and policies intended to encourage the construction of clean energy products are commonplace. Eco-household projects have even been incorporated into the national bond project and are a priority for the Chinese government [62]. In 2007, the Chinese government published the “Medium and Long-term Development Program for Renewable Energy” and revised the “Renewable Energy Law,” which stipulated that the state implement a fully supported system for power generation via renewable energy and became effective on April 1, 2010 [63]. 13th 5-year Plan not only proposed to optimize energy structure and achieve low-carbon development, but also demanded of improving energy system efficiency and development quality with focusing on technological, institutional mechanism and industrial model innovation [64].

However, barriers to biogas project development exist and include relatively weak environmental policies, imperfect financial policies, and lack of long-term follow-through [65]. In regard to environmental protection, it is recommended that increased policy attention be devoted to the storage of straw and dung on farms and ranches, as well as promotion of biogas products to promote waste recycling and using clean energy for reducing the associated environmental pollution. Such a policy has been introduced in Europe, and other countries can learn from this [66,67]. Recycling waste to product biogas is one way to protect the environment; however, if biogas slurry and residue are discharged everywhere instead of being used as organic fertilizer, this will still cause pollution. Thus, it needs to be emphasized that financial subsidies for biogas production should support not only biogas project construction, but also biogas product end use and related services from technicians and companies throughout China [68]. There has been some exploration of methods to support the use of final biogas products and associated services from technicians and professional companies. At present, the economic benefits of biogas projects are not stable, and therefore, government support is needed to reduce the investment risks and uncertainties for the companies implementing the projects, especially in regard to medium- and small-scale biogas projects. The authors think that financial policy support needs to include primarily subsidies for project construction and discounted-interest loans, subsidies for biogas and fertilizer use, and benefits for the connection of biogas power generation to the grid in order to improve the economic efficiency and ensure operation sustainability. For example, the introduction of a biogas power generation green channel policy could encourage biogas projects and protect biogas power generation. Additionally, policies could put forth a directive calling for fertilizer plants and other related industries to enhance the use of by-products.

4.3. Improve ecological-economic benefits

The economic and environmental analysis showed that the use of waste for biogas production would have certain benefits including economic benefits and CO₂ reduction benefits. At the same time, economic and ecological aspects must be considered in order to solve problems in biogas production and maximize benefits. Therefore, it is recommended that changes be implemented in the development model to promote large-scale projects, industrialization, and ecological protection.

Henan is the largest agricultural province in China, and the amount of large-scale animal husbandry is increasing in the region. Presently, most of the waste from large-scale farms is accumulated at random and the sewage is discharged in an unorganized manner. This waste is thus becoming the largest source of pollution in rural areas. In order to

resolve this issue, it is important to promote everything from household and small biogas projects to large- and medium-scale developments. Relevant departments could guarantee the construction of large- and medium-sized biogas projects while improving the standard and quality of biogas plants, which would help to ensure the construction and success of new biogas facilities [69]. Agriculture waste is abundant in Henan Province, and biogas projects mainly use straw and manure as fermentation material; thus, it would be desirable to increase the use of agricultural waste as the main source of raw materials for the construction of biogas projects. In the same way, each region should take its own characteristics as reference and use advantageous raw materials rather than less advantageous materials. Since the construction of a biogas project requires large amounts of capital and an extensive labor force, the authors recommend selecting other utilization modes for waste resources in districts where livestock and poultry manure resources are low, such as Jiyuan City. The selection of suitable agriculture waste, food waste, sewage sludge, and other types of organic waste would help to expand the scale of biogas production.

In addition, the authors think that enterprises should be encouraged to break inter-departmental and regional boundaries and form horizontal alliances. It is also necessary to establish mature biogas engineering products as soon as possible in order to organize full-scale, professional production and increase biogas industrialization. Recycling agricultural models and bioenergy ecological models should be developed in response to the incomplete utilization of biogas engineering; examples might include “4-in-1” and “5-in-1” eco-agricultural orchard systems, which are fully integrated with solar greenhouses and water-saving irrigation systems [70,71]. Use of these ecological recycling principles can lead to potential decreases in reactive nitrogen emissions as well as significant reductions in nutrient pollution [72]. Actively promoting sustainable, cyclical crop cultivation, livestock breeding, and biogas production could extend the biogas industry chain and integrate biogas projects into the development of modern agriculture. For instance, the biogas slurry and residue could be used as fertilizer after treatment, and the potential sources of fermented raw materials could be expanded in order to more efficiently use potential resources [73,74]. The Clean Development Mechanism (CDM) also to learn about advanced technologies from developed countries so as to further reduce greenhouse gas emissions [75]. Priority should be given to advanced technologies, production efficiency, and ecological-economic fermentation demonstration projects to bring about a broader impact.

5. Conclusions and future prospects

This study analyzed the development, tendencies, and existing issues pertaining to biogas in Henan Province, China. By comparing the potential of agricultural waste and biogas project construction, it was found that Henan Province is rich in agricultural waste resources, which could serve as raw materials for biogas production, and it has great biogas potential. By making full use of these wastes, the region could achieve better emission reduction effects and economic benefits. However, the actual production analysis of the biogas plants showed that the plants did not achieve the expected gas production effects. This phenomenon may have been due to low resource utilization and problems in the operation of biogas projects. At the same time, the article proposed solutions to these problems from the technical, policy-based, and ecological-economic perspectives to promote the development of biogas and provide a reference for more regions.

For further biogas development, the authors recommend that Henan Province implement the development model proposed herein. In this paper, biogas potential was estimated from agricultural waste resources. In the future, the biogas potential can be estimated more accurately by combining various wastes with actual research data.

Acknowledgements

This work was supported by Basic Work of Science and Technology Special Project: Survey on Land Utilization and Agricultural Nonpoint Source Pollution Around South-To-North Water Diversion (Mid-Line) (2015FY110400-3); National Natural Science Foundation of China (51508467, 41871205); Natural Science Foundation of Shaanxi Province (2016JQ4007). And thanks for the support of Shannxi Engineering Research Center of Circular Agriculture, and we would like to thank Editage [www.editage.cn] for English language editing. We also thanks for Jun Yang, Miaoping Xu and Weiyu Wang provided help during the writing assistance.

Declarations of interest

None.

References

- Lin Y, Tanaka S. Ethanol fermentation from biomass resources: current state and prospects. *Appl Microbiol Biotechnol* 2006;69:627–42.
- Gao D, Chen TB, Liu B, Zheng YM, Zheng G, Yan-Xia LI. Releases of pollutants from poultry manure in China and recommended strategies for the pollution prevention. *Geogr Res* 2006;25:311–9.
- Guan TTY, Holley RA. Hog manure management, the environment and human health. Berlin: Springer; 2013.
- Sun HS, Yang D, Wei SJ. Analysis on mode and benefit of biogas project on livestock farm. *Adv Mater Res* 2014;955–959:2644–8.
- Congress US Energy policy act of 2005; <https://en.wikipedia.org/wiki/Energy_Policy_Act_of_2005>; 2005 [Accessed 14 March 2018].
- Chen L, Zhao LX, Dong BC, Wan XC, Gao XX. The status and trends of the development of biogas plants for crop straws in China. *Renew Energy Resour* 2010;7–8:145–62.
- Guo XM, Trably E, Latrille E, Carrère H, Steyer JP. Hydrogen production from agricultural waste by dark fermentation: a review. *Int J Hydrog Energy* 2010;35:10660–73.
- Hamelin L, Naroznova I, Wenzel H. Environmental consequences of different carbon alternatives for increased manure-based biogas. *Appl Energy* 2014;114:774–82.
- Crooks AM. Protecting forests and supporting renewable energy. *Biocycle J Compost Recycl* 2005;68–71.
- Holmnielsen JB, Al ST, Oleskowiczpopiel P. The future of anaerobic digestion and biogas utilization. *Bioresour Technol* 2009;100:5478–84.
- QiaoW LiBF, Dong RJ, Sun LY, Li JM. Biogas industry development and renewable energy policy in Germany. *China Biogas* 2016;34(03):74–80.
- Asian Development B. ADB loans support Chinese development of rural biogas energy. *Int Financ* 2010(06):71.
- Deng Y, Xu J, Liu Y, Mancl K. Biogas as a sustainable energy source in China: regional development strategy application and decision making. *Renew Sustain Energy Rev* 2014;35:294–303.
- Tian YS. Potential assessment on biogas production by using livestock manure of large-scale farm in China. *Trans Chin Soc Agric Eng* 2012;28:230–4.
- Ma H, Oxley L, Gibson J, Li W. A survey of China's renewable energy economy. *Renew Sustain Energy Rev* 2010;14:438–45.
- Dang MJ. Output of major farm products. In: Sheng LY, editor. *China Statistical Yearbook*. China Statistics Press; 2014. p. 379–81.
- Dang MJ. Output of major farm products. In: Sheng LY, editor. *China Statistical Yearbook*. China Statistics Press; 2014. p. 386–7.
- Kujawski O, Steinmetz H. Development of instrumentation systems as a base for control of digestion process stability in full-scale agricultural and industrial biogas plants. *Water Sci Technol: J Int Assoc Water Pollut Res* 2009;60:2055–63.
- Linke B, Muha I, Wittum G, Plogsties V. Mesophilic anaerobic co-digestion of cow manure and biogas crops in full scale German biogas plants: a model for calculating the effect of hydraulic retention time and VS crop proportion in the mixture on methane yield from digester and from digestate storage at different temperatures. *Bioresour Technol* 2013;130:689–95.
- Madsen M, Holm-Nielsen JB, Esbensen KH. Monitoring of anaerobic digestion processes: a review perspective. *Renew Sustain Energy Rev* 2011;15:3141–55.
- Mudhoo A, Kumar S. Effects of heavy metals as stress factors on anaerobic digestion processes and biogas production from biomass. *Int J Environ Sci Technol* 2013;10:1383–98.
- Zhang WD, Liu SQ, Zhou B, He CY. National rural organic waste resources and methane potential. *Nat Resour* 1997;19:67–71.
- Li SL, Chang MQ, Zhang GZ, Liu P. Experimental study on biogas production of different stalks anaerobic fermentation. *Mod Agric Sci Technol* 2014;15:218.
- Zhang TT, Feng YZ, Li CZ, Ren GX, Yang GH. The carbon footprint analysis of straw biogas utilization of China in 2011. *J Northwest A&F Univ* 2014;42:124–30.
- Gao WY, Jing-Ming LI, Amp RE, Agency E. Present situation of agricultural bio-energy industry and the effects evaluation. *China Biogas* 2015;33(01):46–52.
- Cao ZH. Research on the potentiality of crop residues in henan province based on energy conversion. *Area Res Dev* 2014;33:163–7.
- Guo YQ. Quantitative appraisal of biomass energy of main crop straw resources and its geographical distribution in Henan Province. *Res Agric Mod* 2013;34(01):114–7.
- Li XF, Li G, Han M, Ge W, Liu S. The research on the estimation of crop straw resource distribution and the resource evaluation in Henan Province. *Henan Science* 2011;29(12):1464–9.
- Zhu CM. Calculation of biomass energy resource of crop residues in Henan Province. *Mod Agric Sci Technol* 2011;07:292–4.
- Li S, Deng LW, Yong Y, Pu XD, Wang ZY. Biogas production potential and characteristics of manure of sheep, duck and rabbit under anaerobic digestion. *Trans Chin Soc Agric Eng* 2010;26:277–82.
- Lin Y, Ma J, Qin F. The structure distribution and prospect of China manure resource. *Chin Agric Sci Bull* 2012;28:1–5.
- Liu D. Gao. The comparison experiment of biogas fermentation with pig dung, cow dung, sheep dung. *J Tarim Univ Agric Reclam* 2005;02:10–2.
- Tian Z, Dong BM, Wei G. Pollution status and biogas-producing potential of live-stock and poultry excrements in China. *Chin J Ecol* 2012;31(05):1241–9.
- Yao AL. Gas potential and characteristics of biogas fermentation raw materials in rural areas in China. *China Biogas* 1988;01:20–4.
- Zhu LJ, Zhao Y. Analysis of methane emission reduction effect and factors on farmers' adoption behavior. *China Popul, Resour Environ* 2012;22(4):35–9.
- Wang GH. Analysis method on reducing emission of SO₂ and CO₂ by rural energy construction. *Trans CSAE* 1999;01:175–8.
- Poeschl Martina, Ward Shane, Owende Philip. Prospects for expanded utilization of biogas in Germany. *Renew Sustain Energy Rev* 2010;14(7).
- Herbes C, Halbherr V, Braun L. Factors influencing prices for heat from biogas plants. *Appl Energy* 2018;221:308–18.
- Ding K, Su YY, Wang YX, Zhang WD. Comprehensive benefit evaluation of rural household biogas based on fuzzy comprehensive evaluation method. *Adv Mater Res* 2013;663:801–6.
- Wang HY, Bi YY, Wang DL, Gao CY, Li JZ, Dang F, Wang YJ. Empirical and simulation analysis on economic feasibility of straw biogas projects for central gas supply. *China Biogas* 2014;32(1):75–8.
- Xiong FL, Zhu HG, Shi HX. Analysis on the price of the biogas for rural centralized biogas plant. *China Biogas* 2011;29(4):16–9.
- UNFCCC Sites and platforms.China.Biennial update reports, <<https://unfccc.int/sites/default/files/resource/chnbur1.pdf>>; 2016 [Accessed 15 March 2018].
- Balat M, Ayar G, Oguzhan C, Uluduz H, Faiz U. Influence of fossil energy applications on environmental pollution. *Energy Sources Part B Econ Plan Policy* 2007;2:213–26.
- Yang Y, Zhang P, Li G. Regional differentiation of biogas industrial development in China. *Renew Sustain Energy Rev* 2012;16:6686–93.
- National Development Reform Commission of People's Republic of China. The National Eleventh Five-year Plan for Environmental Protection (2006–2010). *Environmental Policy Collection*. <<http://www.ndrc.gov.cn/>>; 2018 [Accessed 14 March 2018].
- Zeng X, Ma Y, Ma L. Utilization of straw in biomass energy in China. *Renew Sustain Energy Rev* 2007;11(5):976–87.
- Georgieva TI, Mikkelsen MJ, Ahring BK. Ethanol production from wet-exploded wheat straw hydrolysate by thermophilic anaerobic bacterium *thermoanaerobacter*, BG111 in a continuous immobilized reactor. *Appl Biochem Biotechnol* 2008;145(1–3):99–110.
- Kadirvelu K, Kavipriya M, Karthika C, Radhika M, Vennilamani N, Pattabhi S. Utilization of various agricultural wastes for activated carbon preparation and application for the removal of dyes and metal ions from aqueous solutions. *Bioresour Technol* 2013;87(1):129–32.
- Suthar S. Potential of domestic biogas digester slurry in vermiculture. *Bioresour Technol* 2010;101(14):5419–25.
- Sänger A, Geisseler D, Ludwig B. Effects of rainfall pattern on carbon and nitrogen dynamics in soil amended with biogas slurry and composted cattle manure. *J Plant Nutr Soil Sci* 2010;173(5):692–8.
- Asadullah M. Barriers of commercial power generation using biomass gasification gas: a review. *Renew Sustain Energy Rev* 2014;29(7):201–15.
- Gavala HN, Yenal U, Skiadas IV, et al. Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge. Effect of pre-treatment at elevated temperature. *Water Res* 2003;37(19):4561–72.
- Lemmer A, Merkle W, Baer K, et al. Effects of high-pressure anaerobic digestion up to 30 bar on pH-value, production kinetics and specific methane yield. *Energy* 2017;138:659–67.
- Ashekuzzaman SM, Poulsen TG. Optimizing feed composition for improved methane yield during anaerobic digestion of cow manure based waste mixtures. *Bioresour Technol* 2011;102(3):2213.
- Angelidaki I. Codigestion of manure with lipid containing organic industrial waste. *J Am Med Assoc* 1996;300:1423–31.
- El-Mashad HM, Zhang R. Biogas production from co-digestion of dairy manure and food waste. *Bioresour Technol* 2010;101:4021.
- Ara E, Sartaj M, Kennedy K. Enhanced biogas production by anaerobic co-digestion from a binary mix substrate over a binary mix substrate. *Waste Manag Res* 2015;33:578–87.
- Li YB, Bai JR, Yang GH, Li Y, Guo OY, Ren GX. Influence factors of biogas yields. *J Northwest A&F Univ* 2009;37(05):171–7.
- Weiland P. Production and energetic use of biogas from energy crops and wastes in Germany. *Appl Biochem Biotechnol* 2003;109:263–74.
- Lübken M, Wichern M, Schlattmann M, Gronauer A, Horn H. Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. *Water Res* 2007;41:4085.
- Feng YZ, Guo Y, Yang GH, Qin XW, Song ZL. Household biogas development in

- rural China: on policy support and other macro sustainable conditions. *Renew Sustain Energy Rev* 2012;16:5617–24.
- [62] Bao QH, Bao QH. Problems and countermeasures of national debt projects of rural household biogas 2007(12):55–56.
- [63] National People's Congress of the People's Republic of China. Renewable Energy Law (revision) of P.R. China. http://www.npc.gov.cn/npc/zt/qt/2015zhhsjx/2013-12/04/content_1935957.htm; 2018 [Accessed 14 March 2018].
- [64] National Development Reform Commission of People's Republic of China. The National thirteen Five-year Plan for Environmental Protection (2016–2020). Environmental Policy Collection, <http://www.ndrc.gov.cn/>; 2018 [Accessed 14 March 2018].
- [65] Jiang X, Sommer SG, Christensen KV. A review of the biogas industry in China. *Energy Policy* 2011;39:6073–81.
- [66] Schröder JJ, Neeteson JJ. Nutrient management regulations in The Netherlands. *Geoderma* 2008;144(3–4):418–25.
- [67] Sonneveld MP, Schröder JJ, de Vos JA, Monteny GJ, Mosquera J, Hol JM, et al. A whole-farm strategy to reduce environmental impacts of nitrogen. *J Environ Qual* 2008;37(1):186.
- [68] Fang S. The handicap and strategy of biogas industrialization in rural area of China. *J Agric Mech Res* 2010;32(02):216–9.
- [69] Lin T, Liang X, Xiao C, Liu DY. Study on industrialized biogas management mode. *Renew Energy Resour* 2009;27(01):35–8.
- [70] Qiu L, Yang G, Yang S. A Study into the designs of the optimal ecological orchard project model in the Loess Plateau. *J Northwest Sci-Tech Univ Agric For* 2001;05:65–9.
- [71] Wang CX, Li X, Gao J, Dawa. Four-in-one eco-agricultural model and its application 1998(01):79–81. (in Chinese).
- [72] Artur G, Thomas S, Pentti S, Olof T. Ecological recycling agriculture to reduce nutrient pollution to the Baltic Sea. *Biol Agric Hort* 2008;26:279–307.
- [73] Pan WZ. Analysis of the large farms biogas projects: take the Beijing Deqingyuan Biogas Project as an example. *China Eng Sci* 2011;13:40–3.
- [74] Cheng DS, Feng X. Study on the circular agriculture development in Beijing's mountain areas. *Chin J Popul Resour Environ* 2009;7:55–60.
- [75] Liu DS. Introduction to CDM project development both abroad and in China and analysis to its typical cases. *China Water Power Electr* 2010;9:15–23.